Visual Demonstration of Three-Scale Sea-Surface Roughness Under Light Wind Conditions

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***Abstract*—During the Southern Ocean Waves Experiment (SOWEX) an aircraft carried a down-looking video camera to help document the sea surface. Reflected images of the aircraft were intermittently observed in the video recorded at 15–30-m height under light and variable wind conditions. A numerical simulation was developed to relate image contrast to the gravity-capillary wave contribution to sea-surface mean square slope (mss). "Carnival fun-house" mirror-type distortions of the image in the absence of the gravity-capillary waves relate to intermediate-scale wave persistence when wind forcing stops. Video image estimates of mss correlated better with 36-GHz scanning radar altimeter estimates than with the wind speed measured at 30-m height. When the gravity-capillary waves disappeared in the absence of wind forcing, about one-third of the 0.0015 residual mss was contributed by the dominant waves, and about two-thirds was contributed by the 1–10-m wavelength region. Near the shores of a lake in Alaska, reflected aircraft images were also observed, indicating that the gravity-capillary wave contribution to mss was only about 0.000 001, even though the wind speed at the 160-m aircraft height was 10 m/s.**

***Index Terms*—Light wind, mean square slope (MSS), microwave, optical, sea surface.**

I. Introduction

AREAS of unusually low sea-surface mean square slope (mss) adversely affect almost 6% of the over ocean data of the TOPEX satellite radar altimeter [1]. The unusually high radar cross section of these areas at nadir and its rapid decrease with small increases in incidence angle distort the altimeter return waveform, causing errors in the range measurements. Regions of low wind speed and mss also exhibit an intermittency that adversely affects the measurement of global wind speeds by spaceborne scatterometers [2], [3]. This paper does not investigate either of those phenomena, but describes a new technique accidentally discovered during the Southern Ocean Waves Experiment (SOWEX) [4], [5] which might provide low cost, high spatial and time resolution measurements of sea-surface mss in the gravity-capillary region under conditions responsible for the "σ^0 blooms" of the nadir-looking altimeters and the intermittency affecting the off-nadir-looking scatterometers.

SOWEX was conducted in June 1992 out of Hobart, Tasmania. The National Aeronautics and Space Administration (NASA) Scanning Radar Altimeter (SRA) [6]–[8] was shipped to Australia and installed on a Commonwealth Scientific and Industrial Research Organization (CSIRO) Fokker F-27 research aircraft instrumented to make comprehensive measurements of air–sea interaction fluxes. It also carried a down-looking video camera to help document the sea surface. During a flight under light and variable wind conditions on June 16, reflected images of the aircraft were intermittently observed on the video monitor when the aircraft was at 15–30-m height, which prompted this analysis.

The SRA sweeps a radar beam of 1° (two-way) half-power width across the aircraft ground track over a swath equal to 0.8 of the aircraft height, simultaneously measuring the backscattered power at its 36 GHz (8.3 mm) operating frequency and the range to the sea surface at 64 cross-track positions at measurement angles fixed within ±22° with respect to the normal to the aircraft wings.

The NASA SRA slant ranges are multiplied by the cosine of the off-nadir incidence angles (including the effect of aircraft roll attitude) to determine the vertical distances from the aircraft to the sea surface. These distances are subtracted from the aircraft height to produce a sea-surface elevation map, which is displayed on a monitor in the aircraft to enable real-time assessment of data quality and wave properties. The falloff of backscattered power with incidence angle can be used to determine the sea-surface mean square slope (mss), filtered by the 8.3-mm transmitted wavelength. The light wind during the flight over the Southern Ocean on June 16, 1992 provided an opportunity to relate the mss to the visual appearance of the reflection of the aircraft in the sea-surface imagery captured by a down-looking video camera. This helps put a "face" on the state of the sea surface and its variability under light wind conditions.

Fig. 1 shows the aircraft flight track for a 2.3-h interval on June 16. After leaving the coast of Tasmania at 1.4-km altitude, the aircraft descended to 440 m (***a***). The three small circles

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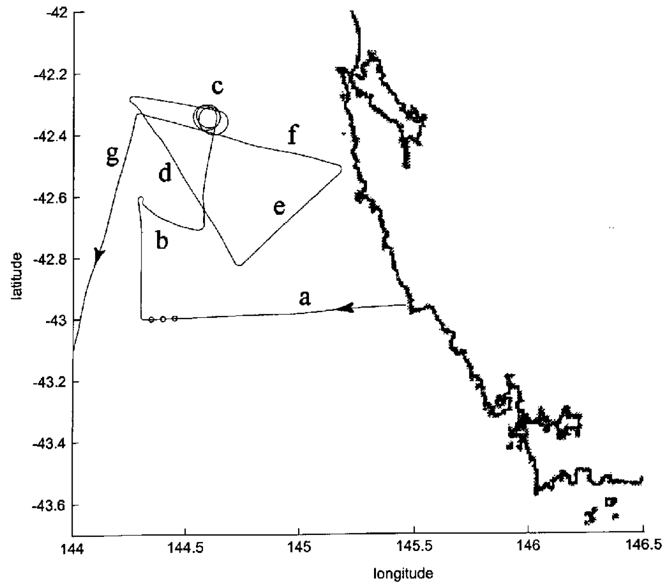

Fig. 1. Flight track of Fokker F-27 aircraft off the western coast of Tasmania, Australia, on June 16, 1992.

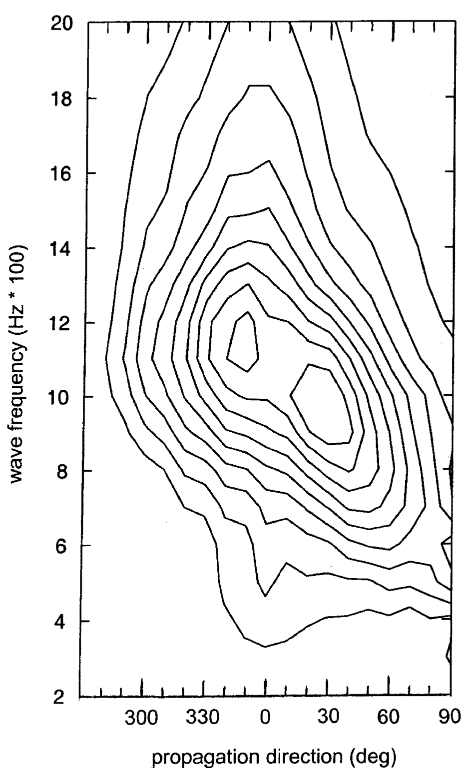

Fig. 2. Average of three directional wave spectra computed from contiguous sea-surface topography spans measured by the SRA, whose centers are indicated by the three circles on flight segment $\boldsymbol{a}$ in Fig. 1. The linear contours span from 0.1–0.9 of the spectral peak density.

indicate the centers of three contiguous SRA data spans used to generate directional wave spectra. The average of the three spectra, additionally smoothed over 0.03 Hz and 30°, is shown in Fig. 2. The significant wave height (H_S) was 2.1 m. The dominant waves had 120–160-m wavelength and propagated toward 350° to 30°. After the aircraft turned north, it dropped to 15-m altitude and did a sounding to 1.5 km $(\boldsymbol{b})$, followed by a series of circles at 240-m altitude to measure the azimuthal dependence of the radar backscatter cross section $(\boldsymbol{c})$. A triangle $(\boldsymbol{d}, \boldsymbol{e}, \boldsymbol{f})$ was flown at 10–15-m height to measure fluxes.

VII. Summary and Conclusion

The present study did not deal with fully developed conditions, but mainly with a light and variable wind in which the gravity-capillary waves exhibited large temporal and spatial variations. It did not attempt to quantify the spectrum, but simply to put an intuitive "face" on the sea surface under those highly volatile conditions.

It is convenient to think in terms of three wavelength scales on the sea surface: small-scale waves, 1–10-m intermediate waves, and large-scale waves. When the small-scale waves damped in the open ocean due to lack of wind or the presence of surfactants, the resulting water surface was smooth enough to reflect an image of an aircraft at a height of 30 m. The reflection still exhibited significant distortions due to the persistence of the intermediate-scale waves which, along with the dominant waves, maintained a minimum mss value of about 0.0015 for the Southern Ocean measurements of this study.

A simple optical model for the small-scale roughness of the water surface as producing an effect beamwidth which diffuses the aircraft image can be used to relate the appearance of the aircraft image in the video to the small-scale mean square slope.

The variation of backscattered power with incidence angle measured by a scanning radar altimeter operating at 36 GHz (Ka-band) provides a very sensitive determination of mss under light wind conditions which should be nearly equal to the optical value. The microwave estimate of mss correlated better with the optical assessment from the aircraft appearance in the down-looking video than it did with the wind speed at 30-m height, as would be expected since they were both direct measures of the surface. In the regions of lowest small-scale optical mss, the 0.0015 microwave minimum value was consistent with the estimate from the visual appearance of the average of the video images which were distorted by the intermediate and large-scale waves.

Despite a 10-m/s turbulent wind at the 160-m aircraft height over a lake in Alaska, the down-looking video image near shore indicated that the small-scale mss was only about 0.000 001. This very low value possibly resulted from a combination of sheltering by the heavily wooded terrain and the presence of surfactants. The absence of intermediate and large-scale waves resulted in an image within a few meters of the shoreline which almost exactly matched the aircraft silhouette.

These data suggest that an automated optical technique for assessing the small-scale mss under light wind conditions could be implemented with a nadir-looking digital camera and an algorithm that related the small-scale mss to the aircraft height and the standard deviation of the image pixels or their frequency content. The aircraft height could be adjusted to optimize sensitivity, flying lower as the average mss increased.

This optical technique would not produce the same level of quantitative data as a laser slope meter, but it might provide low-cost information on mss with high temporal and spatial resolution for investigations that could not afford more sophisticated equipment. Digital video camera data could be sent to a computer over a firewire connection to provide real-time analysis. The technique might even work in a bistatic mode from fixed platforms using a dark target with a series of horizontal and vertical slots of different widths and spacings cut in it to allow the sky light through, after the manner of a traditional optical resolution chart.